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SEISMIC SOURCE REPRESENTATION FOR SPALL

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This technical report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*

Spall may be a significant secondary source of seismic waves from underground explosions. The proper representation of spall as a seismic source is important for forward and inverse modeling of explosions for yield estimation and discrimination studies. We present a new derivation of a widely used point force representation for spall, which is based on a horizontal tension crack model. The derivation clarifies the relationship between point force and moment tensor representations of the tension crack. For wavelengths long compared with spall depth, the two representations are equivalent, and the moment tensor time history is proportional to the doubly integrated time history of the point force. Numerical experiments verify that, for regional seismic phases, this equivalence is valid for all frequencies for which the point-source (long wavelength) approximation is valid. Further analysis shows that the moment tensor and point force representations retain their validity for non-planar spall surfaces, provided that the average dip of the surface is small. The equivalency of the two representations implies that a singular inverse problem will result from attempts to infer simultaneously the spectra of both these source terms from seismic waveforms. If the spall moment tensor alone is estimated by inversion of waveform data, the inferred numerical values of its components will depend inversely upon the source depth which is assumed in the inversion formalism.

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INTRODUCTION

Spall is a widely observed phenomenon accompanying underground nuclear explosions, and its seismic consequences are therefore of considerable interest in the context of verification of test limitation treaties. The proper representation of spall is of importance for forward and inverse seismic modeling of explosions for yield estimation and discrimination studies.

While spall is expected to have negligible effect on long period seismic waves (see Day et al., 1983), several studies suggest that it is a significant contributor to the short period seismic signal from explosions. If this is the case, spall may complicate explosion yield estimates, or at least influence our interpretation of empirically based yield estimation formulas.

For example, the isotropic seismic moment provides one estimate of explosion yield. Patton (1988) used regional, higher mode Rayleigh waves in the 0.2 to 0.5 Hz band to estimate the isotropic moment of the underground explosion HARZER. He concluded that the isotropic moment estimate was sensitive to assumptions about the amount of spall and its efficiency in generating seismic waves in this frequency band.

As a second example, several studies (e.g., McLaughlin, et al., 1988; Taylor and Randall, 1989) have suggested that spall could be a significant contributor to the regional phase Lg, which currently shows great promise as a low-variance yield estimator for explosions at the Soviet Shagan River test site (Hansen et al., 1990). This suggestion arises because spall has a deviatoric source component, which may significantly enhance the production of short period SV waves, compared with the predictions of purely isotropic explosion source models.

Teleseismic P wave amplitudes provide a third basis for yield estimation. At teleseismic distances, the effect of spall is to partially cancel the pP phase, replacing it with an attenuated and delayed phase which is not a replica of the direct P wave (e.g., Day et al., 1986). Schlittenhardt (1990) presents theoretical calculations showing that spall can potentially influence teleseismic P wave amplitudes, given plausible, but uncertain, assumptions about the characteristic mass and momentum of spall.

Day et al. (1983) (hereafter referred to as paper D83) presented a theoretical argument that surface waves of period 20 seconds and longer are not significantly affected by spall. These authors then proposed that the seismic consequences of spall be modeled by a shallow, horizontally oriented tension crack. They analyzed the implications of this model for surface waves with wavelength long compared to the crack dimension and depth, and showed that, in this approximation, the tension crack model was equivalent to a vertically oriented point force acting at the free surface, with the force time history proportional to the crack-separation acceleration history.

The resulting point force model has the property that the model parameters are, at least in principle, observable quantities. The spall mass and momentum, for example, can be estimated from near-field strong motion recordings at the U.S. Nuclear Test Site (NTS) (e.g., Viecelli, 1973; Sobel, 1978; Patton, 1990). This property of relating seismic waves to near-field observables has proven attractive, and the point force model of D83 has been applied extensively (e. g., Stump, 1985; Patton, 1988; Taylor and Randall, 1989), sometimes under conditions which depart significantly from those for which it was originally conceived, namely, low-frequency surface waves.

For this reason, we conclude that a useful purpose is served by presenting a derivation of the point force model which is more general than the original derivation. The new derivation brings out more clearly the relation of the point force representation to the tension-crack model, from which it arises by approximation. The derivation also clarifies the relationship between point force and moment tensor representations for spall, a result which has implications for the explosion-source inverse problem. We then examine numerically the limitations of the point-force representation. Finally, we show that some of the assumptions inherent in the original tension-crack model can be relaxed without requiring revision of the point-force and moment tensor representations.

This paper addresses the seismic representation of spall primarily within the confines of the point source approximation, i.e., wavelength long compared with the characteristic source dimensions. This is the framework within which most previous forward modeling and source inversion has been conducted. The important ancillary effects of lateral finiteness of the spall source will be discussed in a subsequent paper (Barker and Day, in preparation).

TENSION CRACK MODEL

D83 proposed that spall be represented as a horizontally oriented tension crack that opens and closes in the vertical direction (see Figure 1). With the aid of a Green's tensor G, the displacement field u due to a tension crack can be written as a surface integral over the crack surface Σ (Aki and Richards, 1980, p. 39):

$$u_i(x) = \int_\Sigma \nu_j(\xi)\, \delta u_k(\xi)\, C_{jkpq}(\xi)\, G_{ip,q}(x,\xi)\, d\Sigma \ , \tag{1}$$

where ν is the unit normal to the crack, ξ is the general position on Σ, δu is the spall separation,
i. e., the displacement discontinuity across the crack, and C is the elastic tensor. For horizontal crack orientation, vertical spall separation, and crack depth h, (1) can be written in the form

$$u_i(x) = \int_V m_{pq}(\eta) G_{ip,q}(x;\eta)\, d^3\eta \ , \tag{2}$$

where η is the general position in the source volume V, and m is the volumetric moment tensor density,

$$m_{pq}(\eta) = \delta u_3(\eta_1,\eta_2) C_{33pq}\, \delta(\eta_3 - h) \tag{3}$$

($\delta(\cdot)$ is the Dirac delta function). Then, in the point source approximation (wavelength large relative to the maximum dimension of Σ), (2) reduces to

$$u_i(x) = M_{pq} G_{ip,q}(x;0,0,h), \tag{4}$$

where the moment tensor M (volume integral of m) for an isotropic earth model has the following matrix components:

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$$M = \overline{\delta u_3}\, A \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda + 2\mu \end{bmatrix}. \qquad (5)$$

Here $\overline{\delta u_3}$ is the spall separation averaged over the crack area A, and λ and μ are the Lame constants. It will be convenient to refer to (4) and (5) as the *spall moment tensor* representation.

POINT FORCE REPRESENTATION

An expression equivalent to (2) is

$$u_i(x) = \iint \delta u_3(\eta_1,\eta_2)\; T_{33}(\eta_1,\eta_2,h)\, d\eta_1 d\eta_2 , \qquad (6)$$

in which we introduce the notation

$$T_{33}(\eta) = C_{33pq} G_{ip,q}(x;\eta) . \qquad (7)$$

This notation is introduced to emphasize that this factor can be interpreted, by reciprocity, as a component of the stress tensor T induced at the (source) location η in response to a point force (in the i direction) acting at the (receiver) location x. That is, T is simply the stress tensor derived from the elastodynamic displacement field of a point force (note that this usage of the symbol T differs from that of chapters 2 and 3 of Aki and Richards, in which T represents a general traction vector). We expand the η_3 dependence of T_{33} in a Taylor series about the free surface, $\eta_3 = 0$:

$$T_{33}(\eta_1,\eta_2,h) = T_{33}(\eta_1,\eta_2,0) + hT_{33,3}(\eta_1,\eta_2,0) + O(h^2) . \qquad (8)$$

The first term is zero by virtue of the free surface boundary condition. Furthermore, T satisfies the equation of motion, so (in any region which excludes the point x) we have

$$T_{3j,j}(\eta) = -\omega^2 \rho G_{i3}(x;\eta) . \qquad (9)$$

The free surface boundary conditions ensure that $T_{3j,k}$ vanishes, for all j and for k=1,2, in the limit that η_3 goes to zero. Hence, the limiting form of the momentum equation (9) is

$$T_{33,3}(\eta_1,\eta_2,0) = -\omega^2 \rho G_{i3}(x;\eta_1,\eta_2,0)\ . \tag{10}$$

Substituting (10) into the Taylor series (8), and the result into the surface integral representation (6), yields, to first order in the spall depth h,

$$u_i\,(x) = -h \iint \rho\omega^2 \delta u_3(\eta_1,\eta_2)\ G_{i3}(x;\eta_1,\eta_2,0)\ d\eta_1 d\eta_2 \tag{11}$$

In (11), the Green's function is evaluated for source points at the free surface, so that its coefficient

$$\sigma_s = -h\ \rho\ \omega^2 \delta u_3(\eta_1,\eta_2) \tag{12}$$

can be interpreted as a normal traction applied at the *earth's surface* (not the spall surface), with amplitude given by the areal density of the spall layer, ρh, and time history proportional to the acceleration of the spall layer relative to the substrate. The integral (11) thus represents spall as a distributed vertical surface traction; this is an accurate alternative to the moment tensor density representation (2) as long as the higher order terms in the Taylor series (8) are negligible, i.e., when the wavelength is long compared to the source depth. This criterion will frequently be satisfied in practice; for example, for a depth of 150 meters and wavespeed of 3000 m/sec, a quarter wavelength criterion for spall depth corresponds to 5 Hz seismic waves. Numerical experiments discussed below indicate that, in practice, (11) is actually accurate for spall depths up to about half a wavelength.

Finally, in the point source approximation, (11) becomes what we will call the *spall point force* representation:

$$u_i\,(x) = F_s\ G_{i3}(x;0), \tag{13}$$

where the point force amplitude F_s is the surface integral of σ_s, and equals the product of the spall mass m_s and the crack separation acceleration :

$$F_s = -m_s\ \omega^2\ \overline{\delta u_3}\ , \tag{14}$$

$$m_s = \rho\ h\ A\ . \tag{15}$$

Strong motion observations show that the lateral extent of spall typically exceeds its depth by a substantial amount. For example, Patton (1990) finds that, on average, spall radius is roughly a factor of 6 greater than spall depth at the Pahute Mesa area of NTS. As a consequence, lateral finiteness effects will vitiate the point source approximation long before the half wavelength criterion for the spall depth is violated. Thus, the spall moment tensor and spall point force are, in practice, equivalent mathematical representations of the tension crack model. From (5), (14), and (15), it follows that the source spectra M and F_s are related by

$$\mathrm{M}(\omega) = -\frac{\alpha^2}{h\,\omega^2} F_s(\omega) \begin{bmatrix} \lambda/(\lambda+2\mu) & 0 & 0 \\ 0 & \lambda/(\lambda+2\mu) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \qquad (16)$$

where α is the P wave speed. The spall moment tensor time history is α^2/h times the *doubly* time integrated point force time history.

NUMERICAL EXAMPLE

We use regional-distance synthetic seismograms to verify the assertion that the point force and moment tensor formulations are equivalent throughout the frequency range in which lateral finiteness can be neglected. Our focus on regional distance reflects the importance of that distance range for the seismic verification problem. Moreover, regional seismograms contain a complex mixture of wave types, and provide an appropriate test of generality of the purported equivalence of point force and moment tensor. Synthetics are computed using the PROSE code developed by Apsel (1979).

Figure 2 compares synthetic vertical component displacements at 300 km range for the two source representations. The spall separation time history is a delta function, the earth model (Table 1) is the Eastern Kazakhstan crustal model of McLaughlin et al. (1988), and the synthetics are complete for the 0 - 5 Hz frequency band. The point force and moment tensor representations give indistinguishable results for all seismic phases over this pass band when the spall depth is 100 meters. For larger spall depths, the agreement at high frequency only gradually degrades.

Figure 3 compares the Fourier spectra for the two representations, for windows taken around the P_g, L_g, and R_g phases, respectively. Evidently, in the absence of lateral finiteness effects, the spall point force representation is an excellent approximation to the spall moment tensor representation for spall depths up to at least one half wavelength. Patton (1990) found, for Pahute Mesa explosions below the water table, that maximum spall depth was approximately 60 m/kt$^{1/3}$. For a 125 kt event, for example, the point force representation would not be expected to deviate significantly from the moment tensor representation for frequencies less than roughly 2.5 Hz (assuming a near-surface S wave velocity of about 1.6 km/sec, following Bache et al., 1978). As already noted, the point source approximation is invalidated by lateral finiteness effects at considerably lower frequencies than this.

GENERALIZED TENSION CRACKS

In the tension crack model which is the basis of the foregoing analysis, material failure is confined to a horizontal plane. It is possible, however, that in actual explosions, the depth of the detachment horizon may vary laterally across the spall region. For example, Stump (1985) found evidence of variable-depth spall in sub-surface accelerometer recordings of a buried chemical explosion. Furthermore, some numerical simulations of buried explosions indicate spalling over a roughly conical surface, deepest beneath ground zero and shallowing with increasing radial distance from ground zero (see, e.g., Figure 1 of Walton and Heuze, 1989). In such cases, vertical movement of the spall mass implies both normal and tangential components of relative motion across the spall surface. It might be supposed that such an effect would require modification of the spall representations discussed in the previous sections.

However, a simple analysis shows that the spall moment tensor and spall point force representations derived from the horizontal tension crack model will usually be valid even when the spall surface Σ is non-planar, provided (i) spall separation is predominantly vertical, and (ii) the *mean* dip of Σ is small (but arbitrarily rough relief is permitted on Σ). Assumption one is supported by strong motion observations in the spall zone. Likewise, assumption two is supported by the observation that lateral extent of spall generally exceeds its depth by a substantial factor (recall that Patton, 1990, infers a radius to depth ratio of roughly 6). Furthermore, any axisymmetric spall surface has zero mean dip, and any spall surface which terminates by intersecting the earth's surface has, neglecting asymmetric topography, zero mean dip.

To verify the assertion that the moment tensor and point force derived from the horizontal tension crack have this more general validity, we take the spall depth to be a given function $h(\eta_1,\eta_2)$ of the horizontal coordinates, so that the spall surface is specified by

$$\eta_3 - h(\eta_1,\eta_2) = 0 \,. \tag{17}$$

The representation theorem (1) becomes

$$u_i(x) = \int_\Sigma \delta u_3 \, \nu_j \, C_{j3pq} \, G_{ip,q} \, d\Sigma$$

$$= \iint \delta u_3 \, \nu_j \, C_{j3pq} \, G_{ip,q} \frac{d\eta_1 d\eta_2}{\nu_3} \,. \tag{18}$$

(the double integration is over the projection of Σ onto the η_1, η_2 plane). We decompose the summation on j, which is implicit in (18), into two parts. The first part, I_V, corresponds to $j = 3$ (vertical component of the normal vector ν), the second part, I_H, corresponds to $j = 1, 2$ (horizontal components of ν):

$$u_i(x) = I_V + I_H, \tag{19}$$

in which

$$I_V = \iint \delta u_3 \, T_{33}(\eta_1,\eta_2,h(\eta_1,\eta_2)) d\eta_1 d\eta_2 \,, \tag{20}$$

$$I_H = \iint \delta u_3 \; T_{3\alpha} \frac{\nu_\alpha}{\nu_3} d\eta_1 d\eta_2 \,, \tag{21}$$

where $\alpha = 1, 2$, and the summation convention on α applies. The first term, I_V, is analogous to our result for the simple tension crack, and can be transformed to a surface traction representation by the same steps leading to (11-12):

$$I_V = \iint \sigma_s(\eta_1,\eta_2) \, G_{i3}(x;\eta_1,\eta_2,0) \, d\eta_1 d\eta_2 \,, \tag{22}$$

where σ_s is the surface density of the (variable-depth) spall layer times the spall acceleration,

$$\sigma_s = -\rho h(\eta_1,\eta_2)\omega^2 \delta u_3(\eta_1,\eta_2) \quad . \tag{23}$$

In the point source approximation, we obtain the analogue of (13-15),

$$I_V = F_s\, G_{i3}(x;0) \quad , \tag{24}$$

where

$$F_s = \iint \sigma_s(\eta_1,\eta_2)\, d\eta_1 d\eta_2 \quad . \tag{25}$$

The second term, I_H (Equation 21), can be transformed using the identity

$$\frac{\nu_\alpha}{\nu_3} = \frac{\partial h}{\partial \eta_\alpha} \quad , \tag{26}$$

to give

$$I_H = \iint \delta u_3\, T_{3\alpha} \partial_\alpha h\, d\eta_1 d\eta_2 \quad . \tag{27}$$

Since $T_{3\alpha}$ vanishes at $h = 0$, (27) is, to first order in h,

$$\begin{aligned} I_H &= \iint h \partial_\alpha h\, \delta u_3\, T_{3\alpha,3}\, d\eta_1 d\eta_2 \\ &= \iint \partial_\alpha \phi\, \delta u_3\, T_{3\alpha,3}\, d\eta_1 d\eta_2 \end{aligned} \quad , \tag{28}$$

where

$$\phi = \frac{1}{2} h^2 \quad . \tag{29}$$

In the point source approximation, (28) becomes

$$I_H = T_{3\alpha,3} \iint \partial_\alpha \phi \, \delta u_3 \, d\eta_1 d\eta_2 \quad , \tag{30}$$

and if we add the assumption that δu_3 is uncorrelated with $\partial_\alpha \phi$, then we can factor the mean spall separation $\delta \bar{u}_3$ out of the integral in (30). The result is

$$I_H = \frac{1}{2} \delta \bar{u}_3 T_{3\alpha,3} \oint h^2 \gamma_\alpha \, dl \quad , \tag{31}$$

where the line integral is over the periphery of the projection of the spall surface Σ onto the horizontal plane, and $\hat{\gamma}$ is the unit (two-dimensional) outward normal to this curve (lying in the η_1, η_2 plane). The line integral in (31) vanishes whenever the spall surface is bounded by a level curve, and will be small whenever the mean dip of the spall surface is small. The latter interpretation follows if h is expanded to first order about the mean depth, h_0. Then the integral reduces to $h_0 A d_\alpha$, where A is the (projected) area of spall, and d_α is the average value of the slope $\partial_\alpha h$. Thus, it is likely that I_H can be neglected in most cases of interest. The remaining term, I_V, is identical to the point force representation for the simple crack, as shown by comparing (24-25) with (13-15) (although we can no longer factor F_s, Equation 25, into the product of spall mass and average acceleration, unless δu_3 and h are uncorrelated in η_1, η_2).

DISCUSSION

D83 derived the point force representation (Equations 13 - 15) for the special case of Rayleigh waves. The present derivation justifies the subsequent application of the point force representation, by numerous authors, to model other seismic phases (i.e., the approach is justified to the extent that the generalized tension crack approximates the geometry of actual spall, the separation function δu_3 is appropriately prescribed to represent the kinematics of spall, and the wavelength limitation is honored). The derivation also serves to underscore that fact that, while the spall moment tensor is located at spall depth, the spall point force is located at the earth's surface.

The derivation makes clear the redundancy of representing spall using both the spall moment tensor *and* the spall point force concurrently; since the two are equivalent, any attempt to infer simultaneously the spectra of both of these source terms from seismic waveforms will lead to a singular inverse problem. This was previously noted by Stump (1987, 1990) on the basis of numerical experiments. Generally, a singular inverse problem will result if the point force representation is combined with *any* moment tensor representation from which (5) can be constructed by linear combination.

Equation 16, which expresses the correspondence between the source spectra $M(\omega)$ and $F_s(\omega)$, has an additional consequence which should be noted. If $M(\omega)$ is estimated by inversion of seismic data (e. g., Stump, 1988, 1990; Johnson, 1988), the numerical values associated with $M(\omega)$ are expected to depend inversely upon the source depth which is assumed for the inversion (whereas inversion for $F_s(\omega)$ does not incorporate an assumption of source depth). This point becomes important when inversions based on the two alternative representations are compared quantitatively , as they sometimes have been in the seismic literature on spall.

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REFERENCES

Aki, K. and P. G. Richards (1980). *Quantitative Seismology, Vol. I*, W. H. Freeman and Company, San Francisco.

Apsel, R. J. (1979). Dynamic Green's functions for layered media and application to boundary-value problems, *Ph.D. Thesis*, University of California, San Diego.

Bache, T. C., W. L. Rodi, and D. G. Harkrider (1978). Crustal structures inferred from Rayleigh-wave signatures of NTS explosions, *Bull. Seism. Soc. Am. 68*, 1399-1413.

Day, S. M., N. Rimer, and J. T. Cherry (1983). Surface waves from underground explosions with spall: Analysis of elastic and nonlinear source models, *Bull Seism. Soc. Am. 73*, 247-264.

Day, S. M., N. Rimer, T. G. Barker, E. J. Halda, and B. Shkoller (1986). Numerical study of depth of burial effects on the seismic signature of underground explosions, S-Cubed report DNA-TR-86-114, July.

Hansen, R. A., F. Ringdal, and P. G. Richards (1990). The stability of RMS L_g measurements, and their potential for accurate estimation of the yields of Soviet underground nuclear explosions, NTNF/NORSAR Report GJL-TR-90-0061, February. ADA 222186

Johnson, L. R. (1988). Source characteristics of two underground nuclear explosions, *Geophys. J. 95*, 15-30.

McLaughlin, K. L., T. G. Barker, S. M. Day, B. Shkoller, and J. L. Stevens (1988). Effects of depth of burial on explosion and earthquake regional seismograms: regional discrimination and yield estimation, S-CUBED report SSS-R-88-9844, La Jolla, California.

Patton, H. J. (1988). Source models of the Harzer explosion from regional observations of fundamental-mode and higher mode surface waves, *Bull. Seism. Soc. Am. 78*, 1133-1157.

Patton, H. J. (1990). Estimates of spall mass and spall impulse from observed strong ground motions on Pahute Mesa, submitted to *Bull. Seism. Soc. Am.*

Schlittenhardt, J. (1990). The effects of spall on teleseismic P-waves: An investigation with theoretical seismograms, submitted to *AGU Monograph on Explosion Source Phenomenology.*

Sobel, P. A. (1978). The effect of spall on m_b and M_S, Teledyne Geotech Report SDAC-TR-77-12, Dallas, Texas.

Stump, B. W. (1985). Constraints on explosive sources with spall from near-source waveforms, *Bull. Seism. Soc. Am. 75*, 361-377.

Stump, B. W. (1987). Mathematical representation and physical interpretation of a contained chemical explosion in alluvium, *Bull. Seism. Soc. Am. 77*, 1312-1325.

Stump, B. W. (1990). Resolution of complex explosive source functions in the frequency domain, in press, *Geophys . J.*

Taylor, S. R. and G. E. Randall (1989). The effects of spall on regional seismograms, *Geophys. Res. Letters 16*, 211-214.

Viecelli, J. A. (1973). Spallation and the generation of surface waves by an underground nuclear explosion, *J. Geophys. Res. 78*, 2475-2487.

Walton, O. R., and F. E. Heuze (1989). Discrete element modeling of explosions in jointed rocks, in Patton, H. J., and Taylor, S. R. (Eds.): *Proceedings of the DOE/LLNL Symposium on Explosion-Source Phenomenology,* Lawrence Livermore National Laboratory Report No. CONFERENCE-890398.

FIGURE CAPTIONS

Figure 1. Geometry of the tension crack spall model.

Figure 2. Synthetic seismograms for the point force and moment tensor representations. Sources for the 4 depths h have been scaled to constant spall mass ρhA .

Figure 3. Fourier spectral ratios for the synthetics shown in Figure 2. Separate spectra are shown for time windows about the P_g, L_g, and R_g phases, respectively.

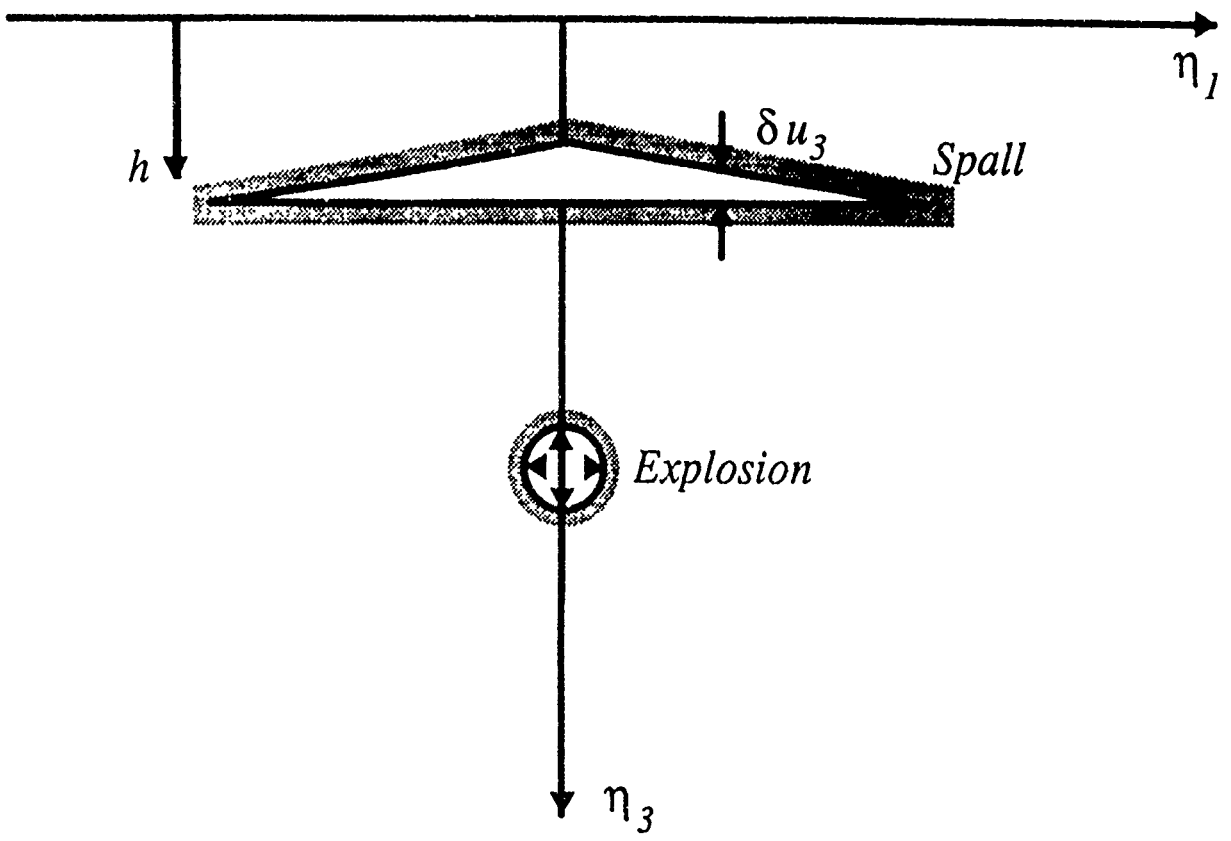

FIGURE 1

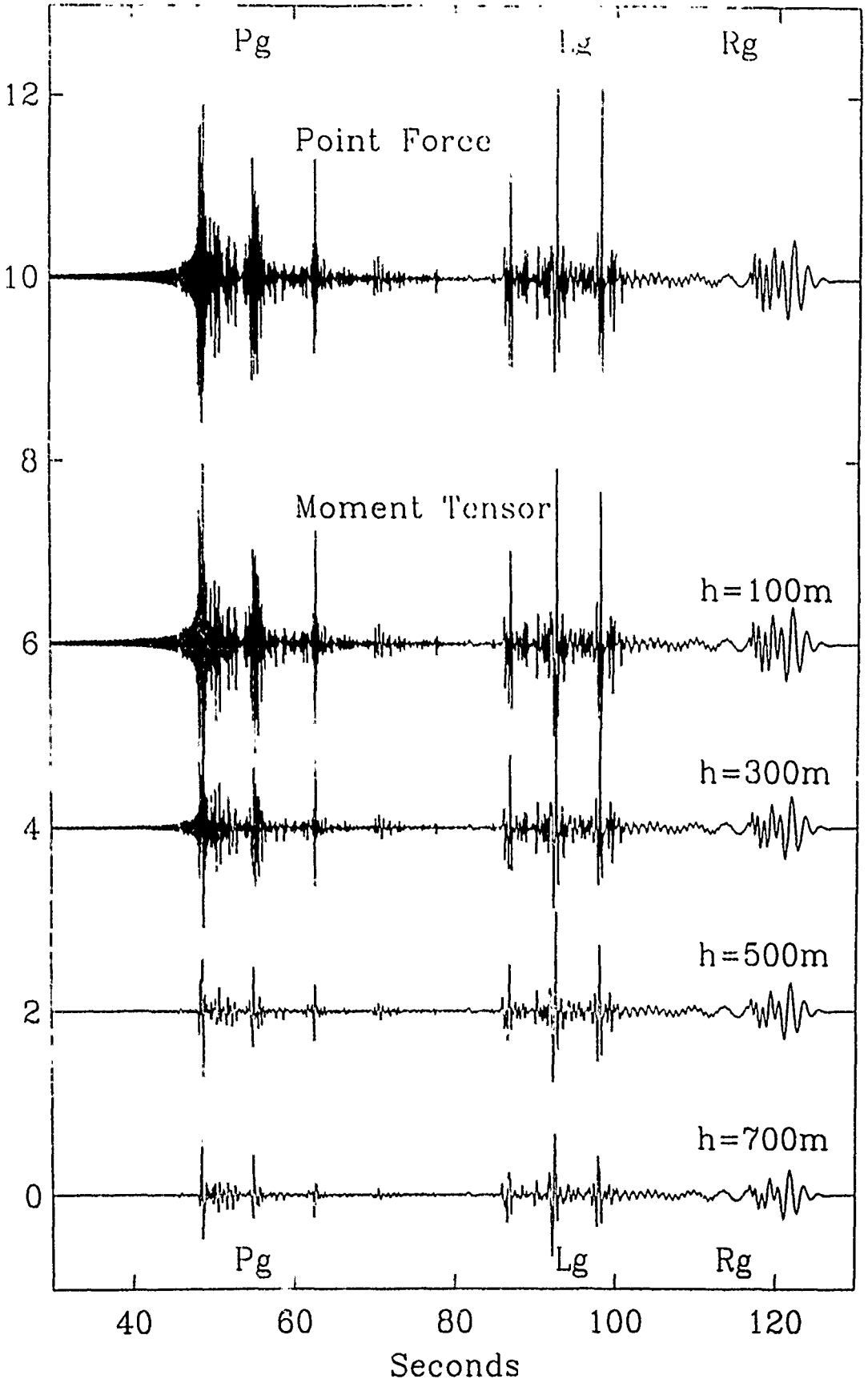
Spall Representations (Vertical, 300 Km, 0 to 5 Hz)
Pg
Lg
Rg
12
Point Force
10
8
Moment Tensor
h=100m
6
h=300m
4
h=500m
2
h=700m
0
Pg
Lg
Rg
40
60
80
100
120
Seconds

FIGURE 2

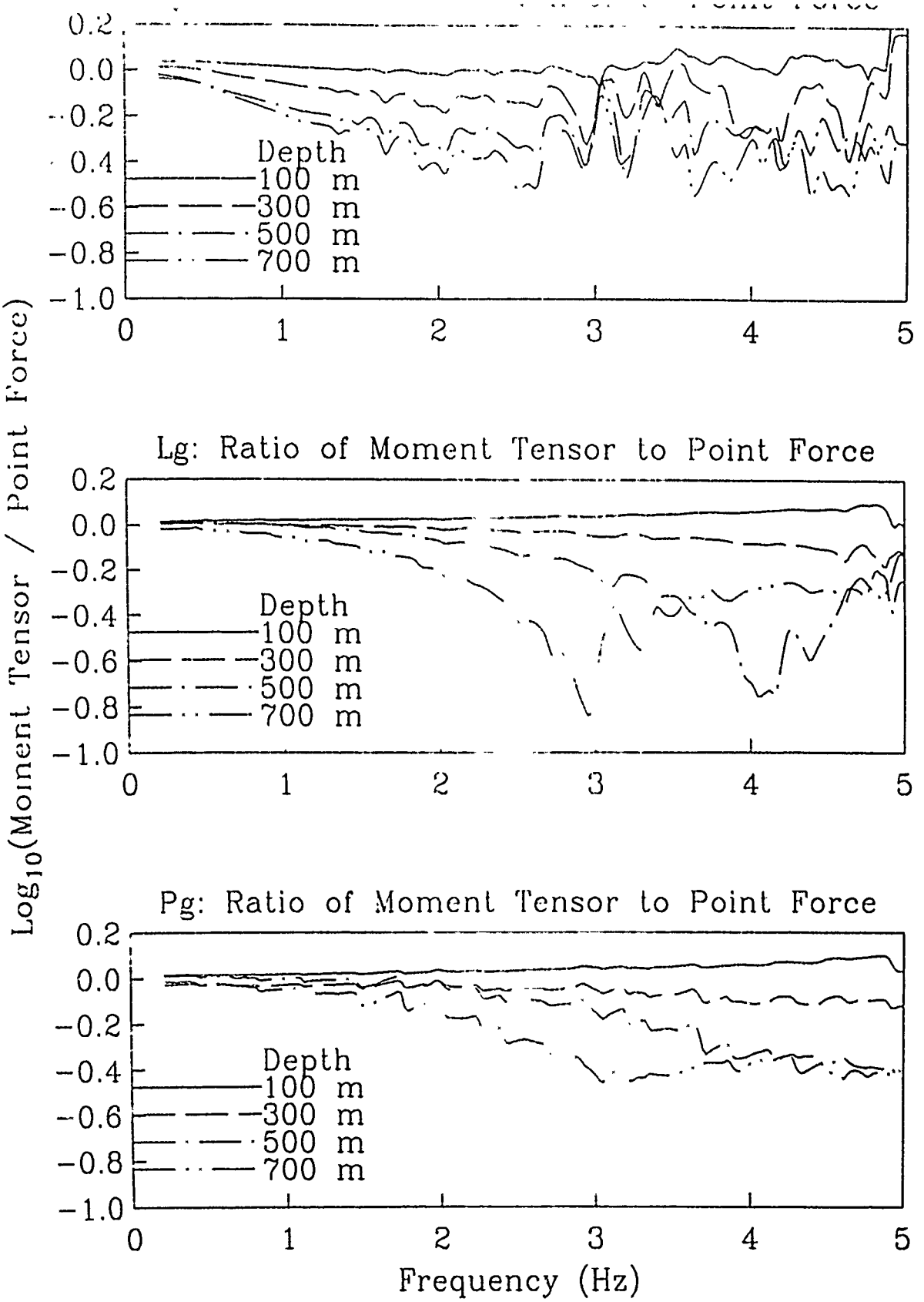
Lg: Ratio of Moment Tensor to Point Force
Pg: Ratio of Moment Tensor to Point Force
Depth
100 m
300 m
500 m
700 m
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0
1
2
3
4
5
Log10(Moment Tensor / Point Force)
Frequency (Hz)

FIGURE 3

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